Large Format Bolometer Arrays for Far-IR and Sub-MM Astronomy

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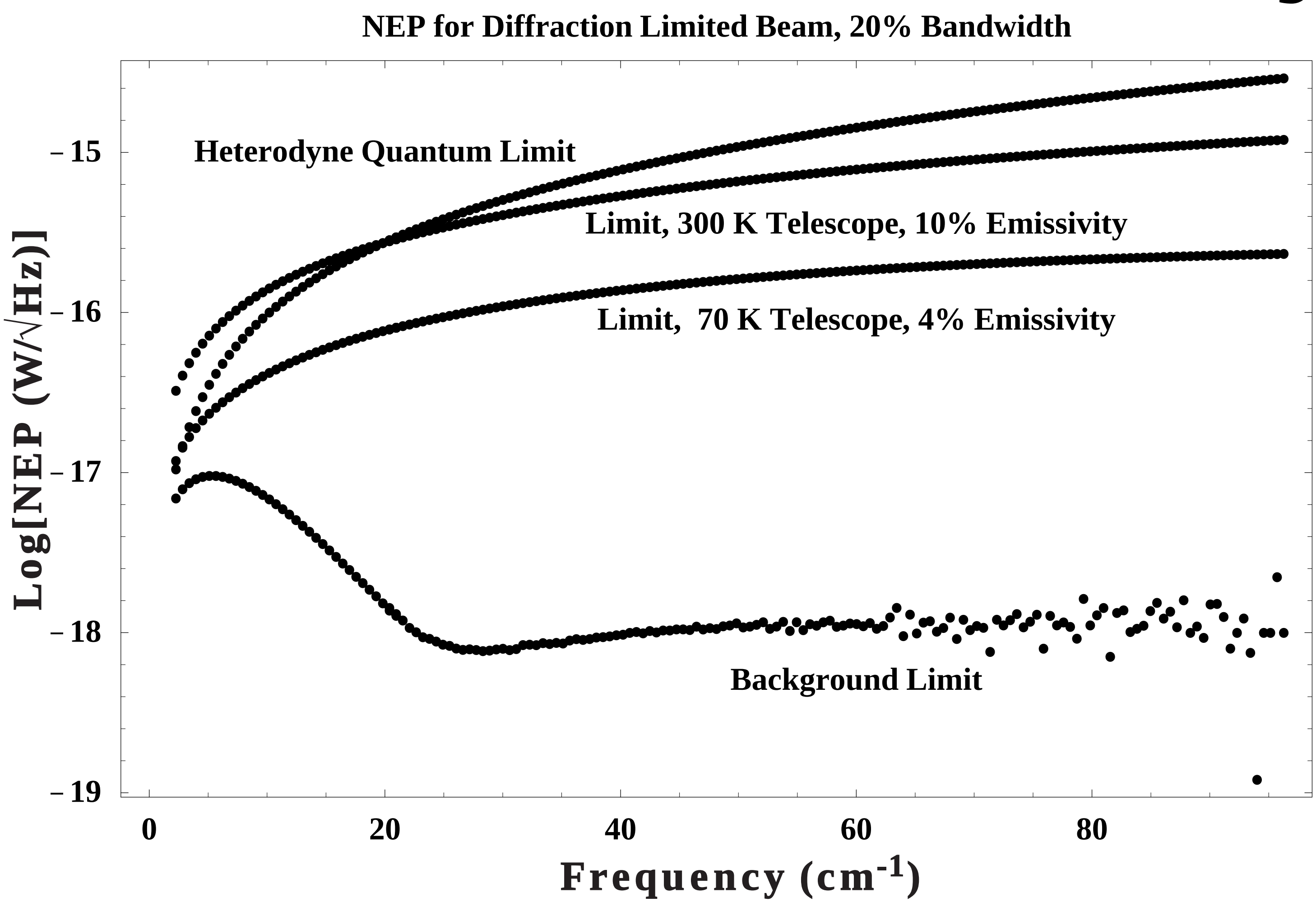
Planned Missions Require High Performance Thermal Detectors

- NASA's road map includes missions which require high performance long wavelength direct detectors

– SOFIA	2004
– The Einstein Inflation Probe -	2007
– SAFIR -	2011
– SPECS/SPIRIT	2018?
– Explorers/Discovery	2005

Limits to Sensitivity



Detector Parameters Required

- NEP — 10^{-16} - 10^{-20} W/Hz
  - T_{op} — ~ 0.04 - 0.3 K
- Quantum Efficiency — high (~> 0.9)
- Wavelength range — 40 μm to ~ 4 mm
- Detector format — 10^3 to 10^4 pixels

System Performance Drivers

- Survey Speed of a background limited IR Imager scales as:
  - – Detector Quantum Efficiency
  - – Total detector AΩ (number of detectors)
- Bolometers can offer high efficiency
- Large format arrays already produced, very large possible with multiplexing technologies

Outline

- Thermal Detector Basics
- Individual Detector Design, Optimization, and Production
  - Semiconductors Pop-up arrays with JFET readout
    - Deep Diffusion,NTD Ge
  - TES-based detectors
- Detector architectures and necessary developments.

Production and Test Capability

- Production capabilities in NASA/University labs; no related commercial products
- Testing is difficult now, will become a major challenge as detectors become more sensitive. Ground-based, airborne, and balloon validation possible for higher background devices.

Thermal Detector Basics

- Detect radiant power by measuring the temperature rise of the detector due to absorption of the incident radiation
- Sensitivity set by
  - efficiency of coupling of radiant power to detector (and rejection of unwanted light)
  - noise of detector (typically set by thermodynamics) or of detected photon stream

Coupling to Far Infrared Radiation

- Technique for power absorption is a design choice dictated by the application
  - Resistive absorber
    - Instrument optics limits AΩ
      - Broad Simultaneous wavelength coverage (HAWC)
  - Concentrators
    - Multimode (e.g.,Winston Cones)
    - Single mode
      - Feedhorn or planar antenna
- Calculations of optical coupling can be done reliably, and provide excellent basis for design

Choice of Thermometer

- The sensitivity of an ideal thermal detector depends on the temperature coefficient of the thermometer element.
  - $\delta E = NEP(\tau^{1/2}) = \zeta\, \alpha^{-1/2} (k\, T^2\, C)^{1/2}$
  - $\alpha = d(\log R)/d(\log T) = T/R\ dR/dT$
  - $NEP = \chi\, (k\, T^2\, G)^{1/2}$
- Practical consideration, such as availability of low noise amplifiers and ability to produce thermodynamically limited devices dictates the selection of thermometers.

Semiconducting Bolometers

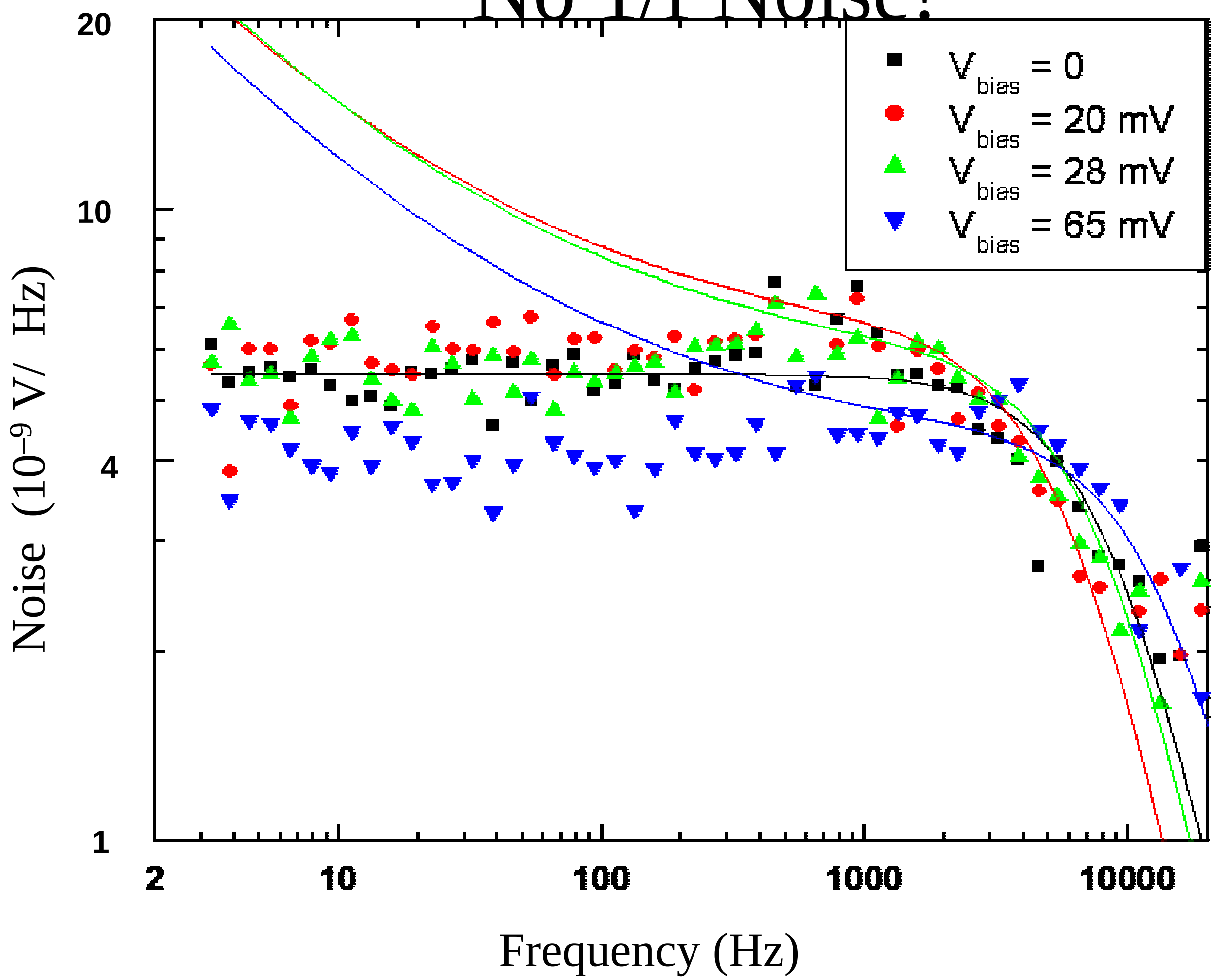
- Most systems now operating use semiconducting thermometers read out by JFET amplifiers.
  - Ion implanted Si
    - Easily integrated into wafer-scale micromachined structures
    - Diffused devices, no detectable 1/f noise
  - NTD Ge
    - Low 1/f noise
    - Good repeatability

Physics of Thermometers

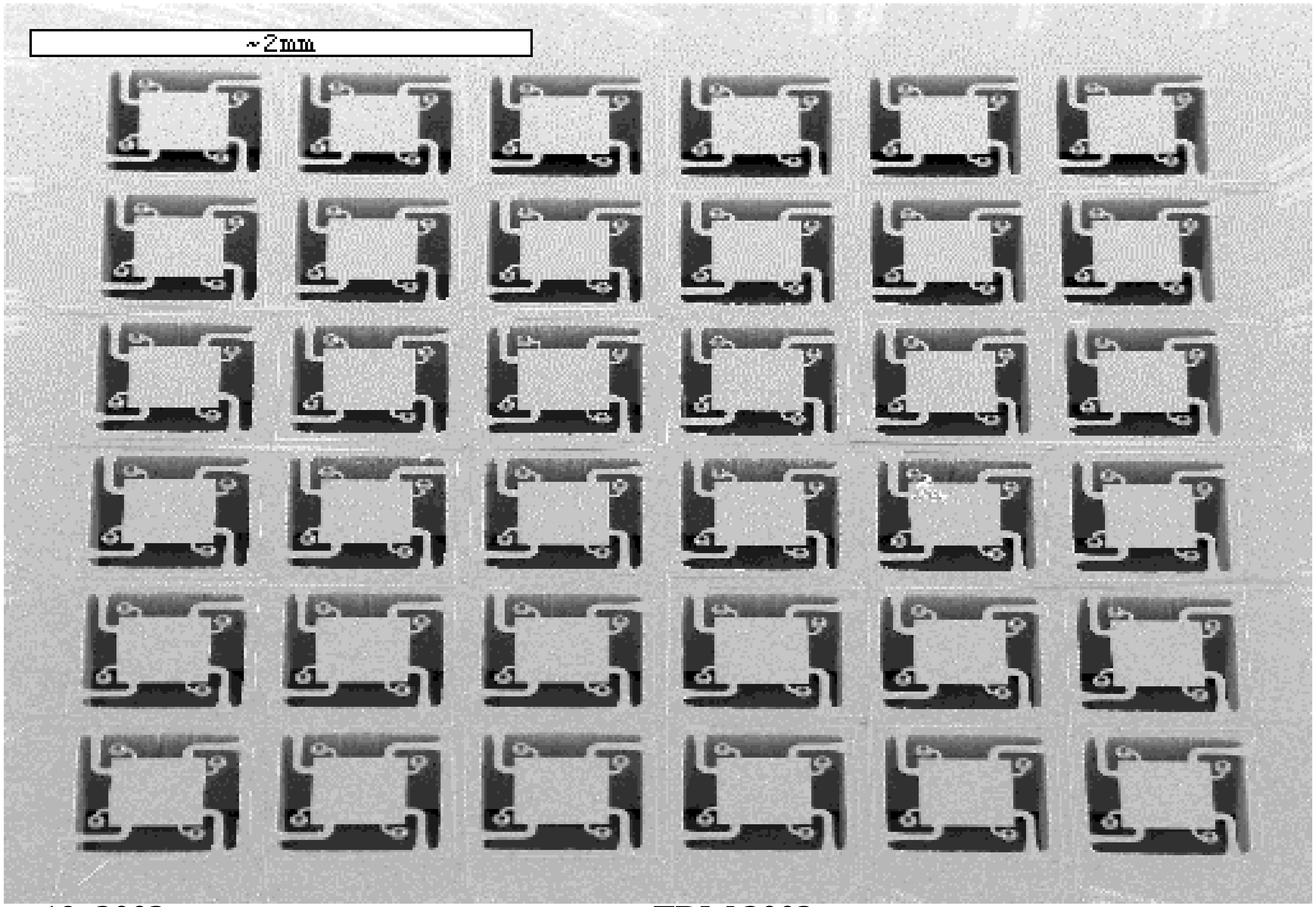
- Semiconductor thermometers have “nonideal” behaviors
  - Minimum detector volume set by electron-phonon decoupling (see McCammon et al., LTD 9, Zhang et al. 1998, Wang, 1991)
- Thin Si implants show measurable, predictable 1/f noise (Han et al. 1998)
- Thick diffused Si implants show no measurable 1/f noise even when bias significantly heats electron system.

Noise of 1.5 µm Diffused Implant

No 1/f Noise!



XRS Propotype Array



Semiconducting Thermometers Conclusion

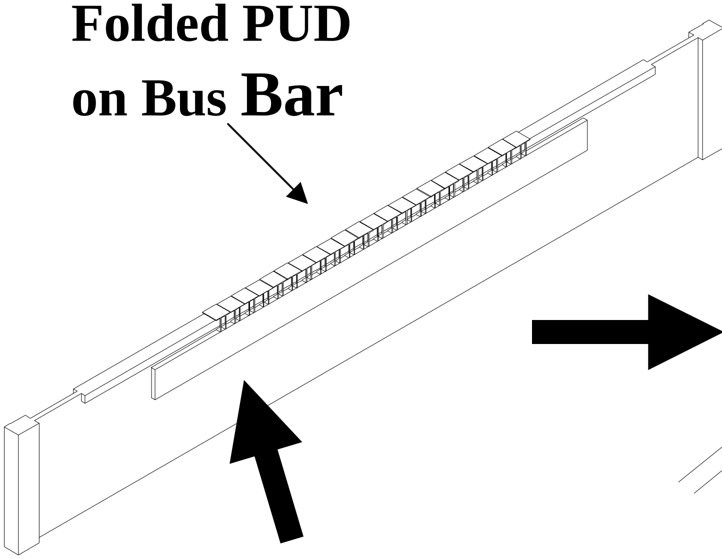
- Thermometer physics is well enough understood to allow *ab initio* design of optimal, micromachined detectors for specific applications
- For T >~ 0.05K;
  - Conventional detectors possible down to
  - ~3 10^{-19} W/Hz $^{1/2}$
  - Small Hot Electron devices can operate down to 10^{-20} W/Hz $^{1/2}$
- Integration with amplifiers biggest problem

Pop-up Detectors for HAWC

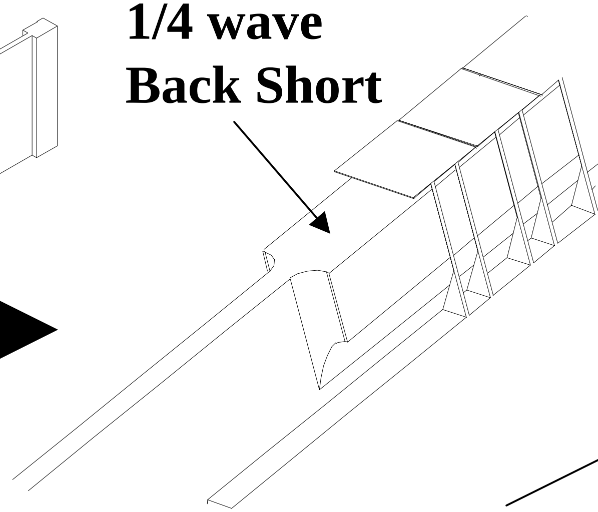
- Large format required
  - 12 x 32 goal
- Nyquist sampling of psf
- Broad spectral coverage (4 bands, 50 - 250 μm)
  - Sampling maintained by magnification change
- Semiconducting Pop-up selected
  - Engineering model built, tested in SHARC II camera

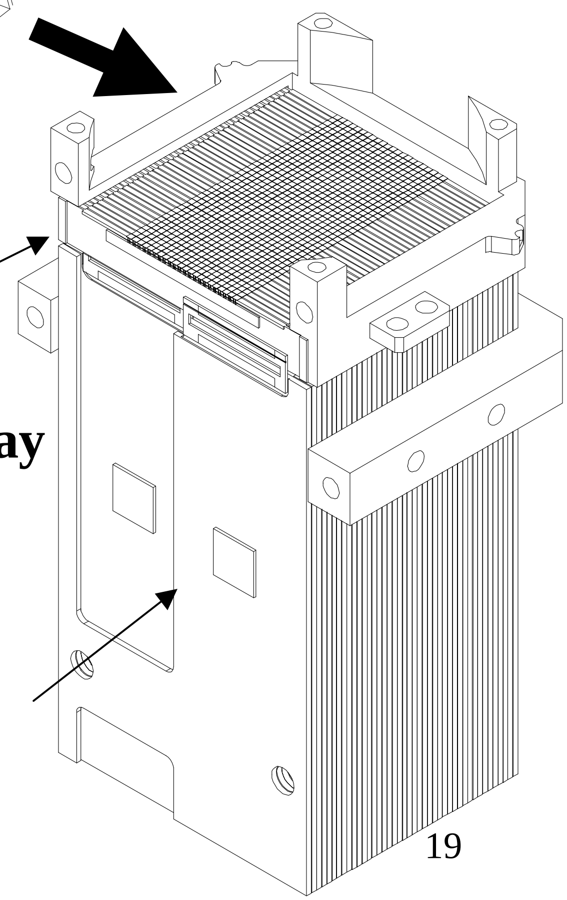
Pop-up Assembly **Process**

Folded PUD on Bus Bar



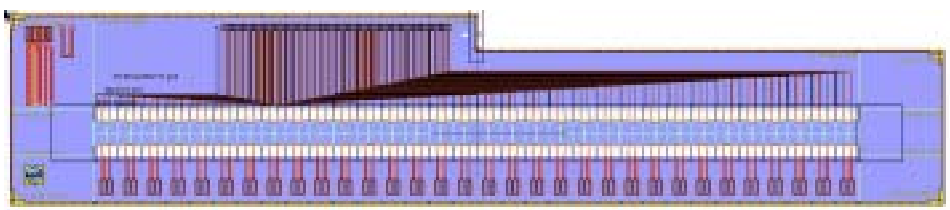
1/4 wave Back Short





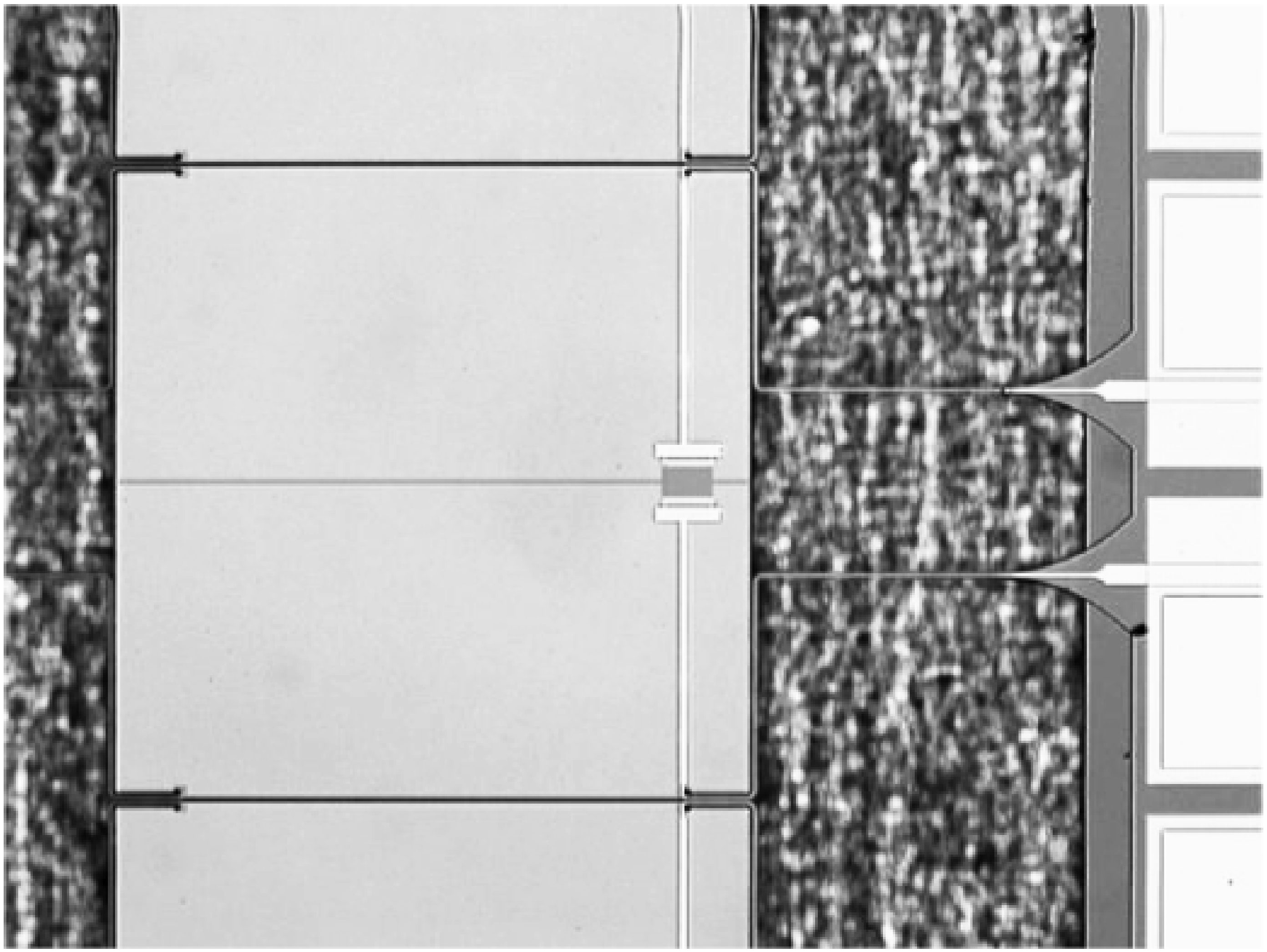
Bus Bar in stacked array

Fanout Boards

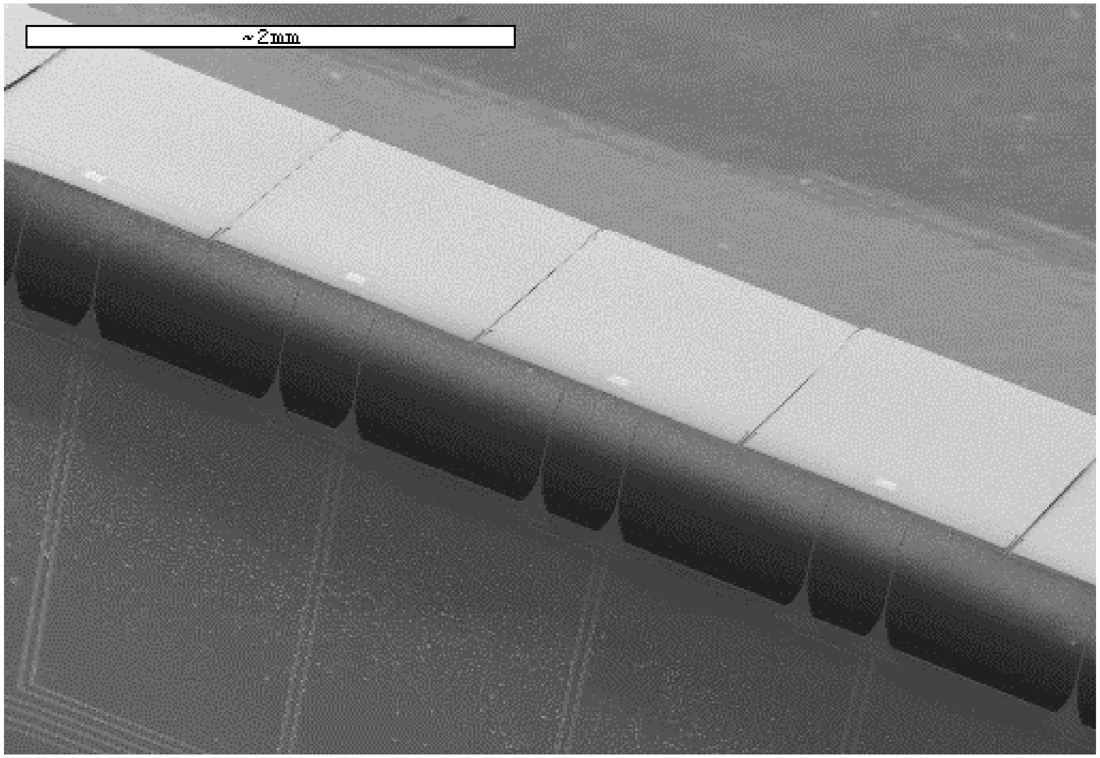


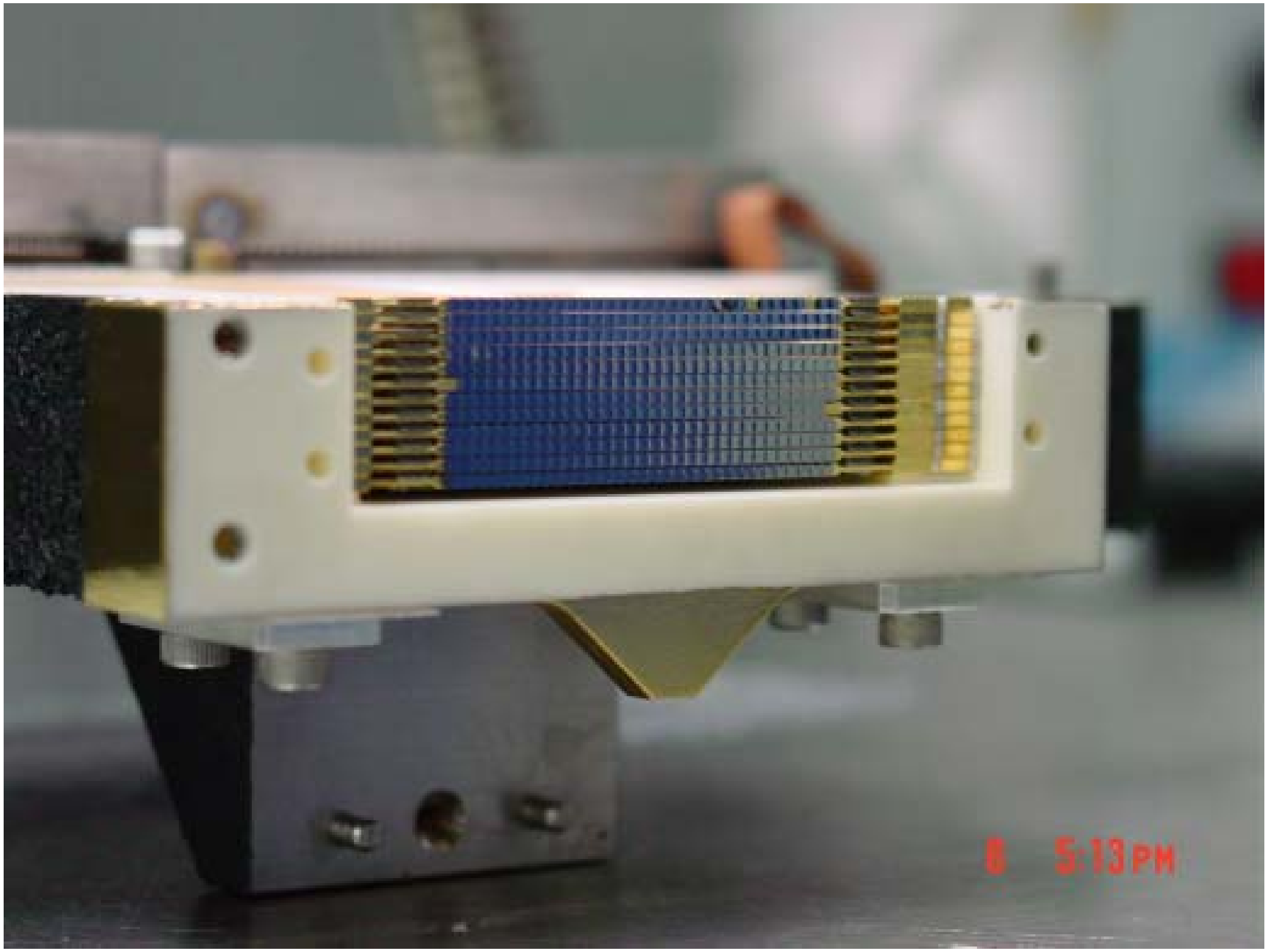
Pre-folded PUD

Unfolded Pop-up



Folded Linear Bolometer Array

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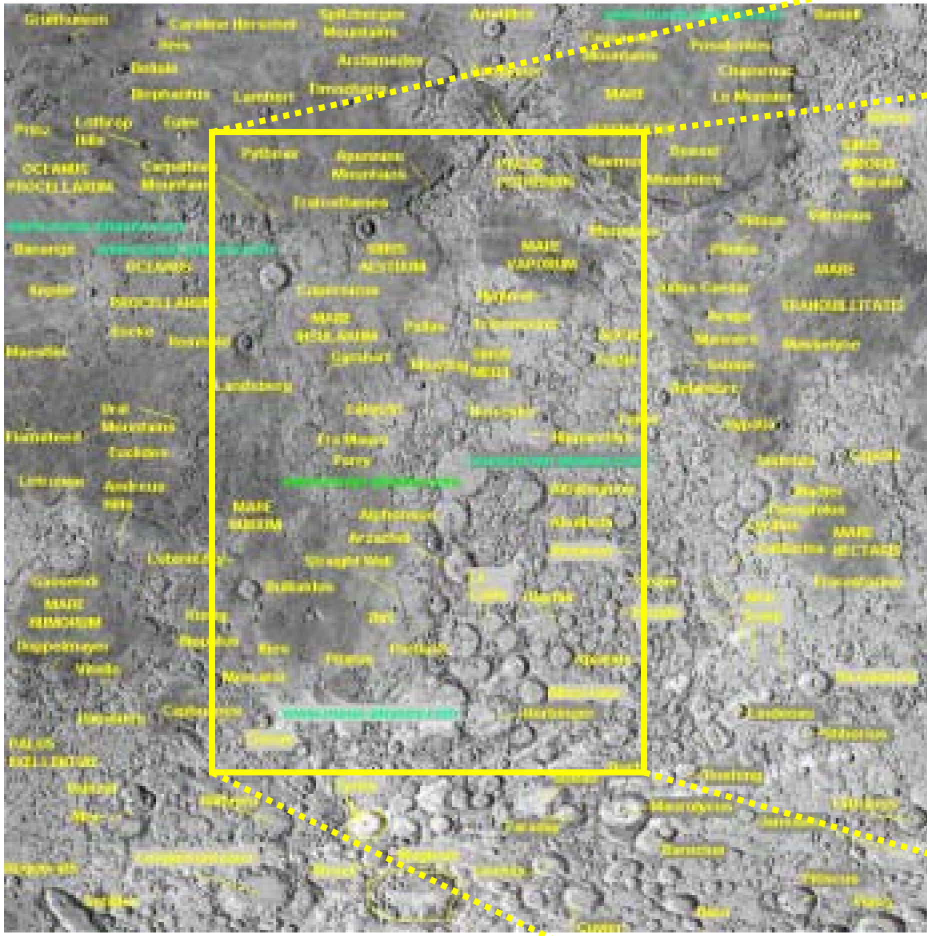
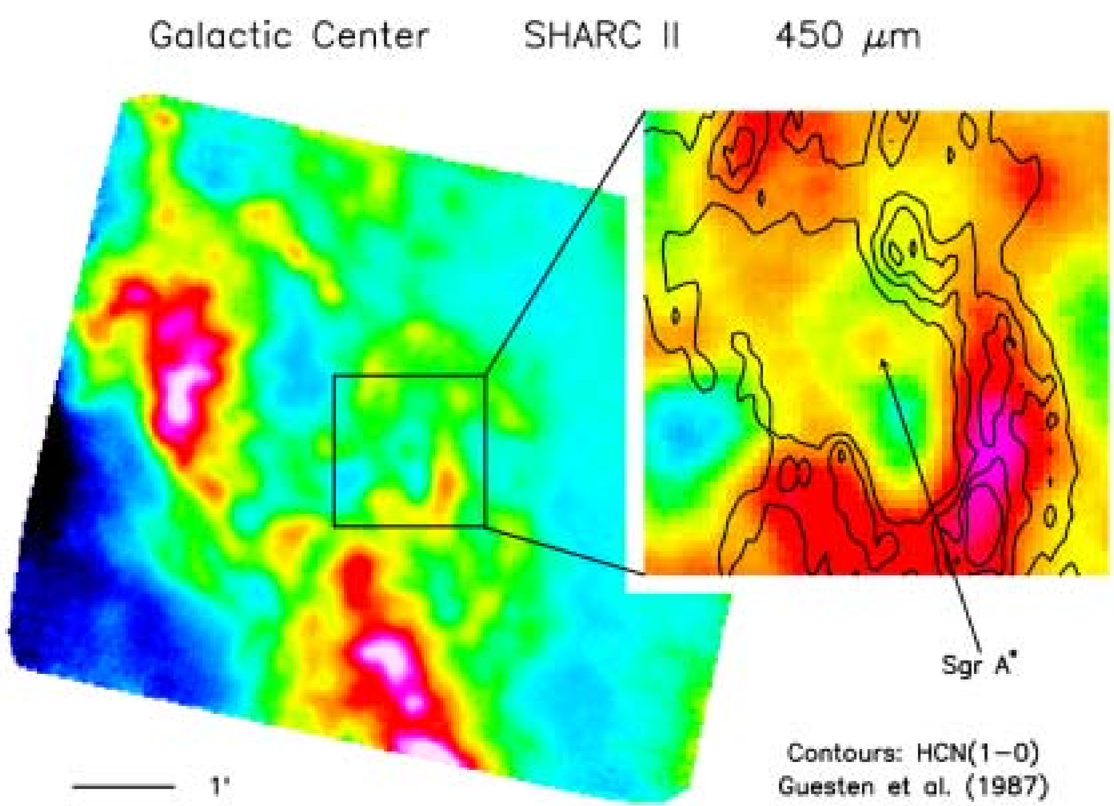
SHARC II Imaging

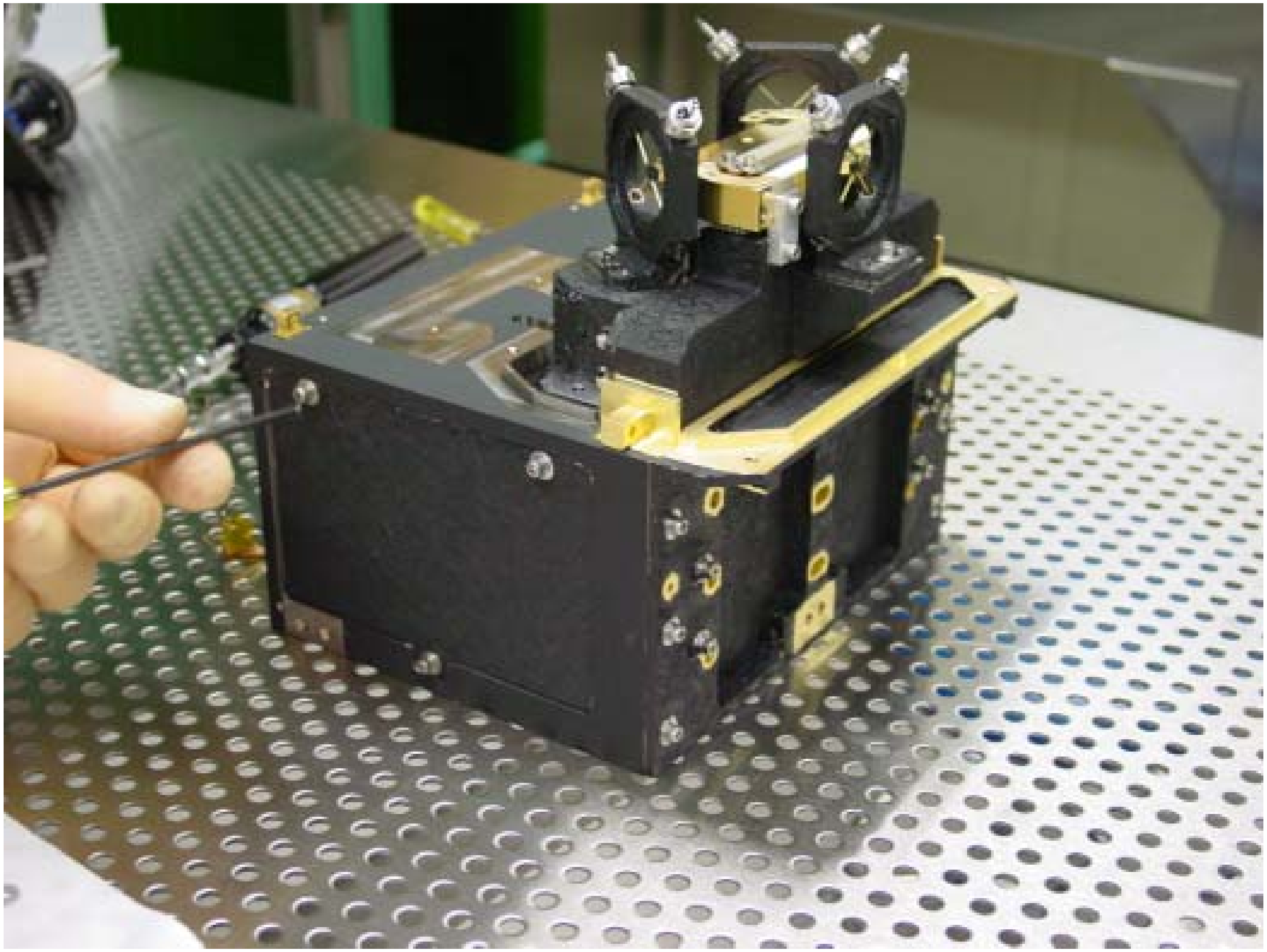


SHARC II produces high quality image of a familiar astronomical object.

SHARC-II Image of the Galactic Center



Benford, Dowell, and Staguhn, in prep.



HAWC/SHARC Summary

- SHARC II operating as CSO facility instrument, sensitivity near design predictions
- Design mechanically and thermally sound

- HAWC In assembly, absorbers being deposited

TES Bolometers
A Path Towards Large Format Arrays

- TES detectors and SQUID amplifiers offer significant benefits for large format arrays.
  - High performance thermometer
  - Couple naturally to SQUID amps
    - SQUIDs happy from detector temp to 4.2K
  - Capability of multiplexing

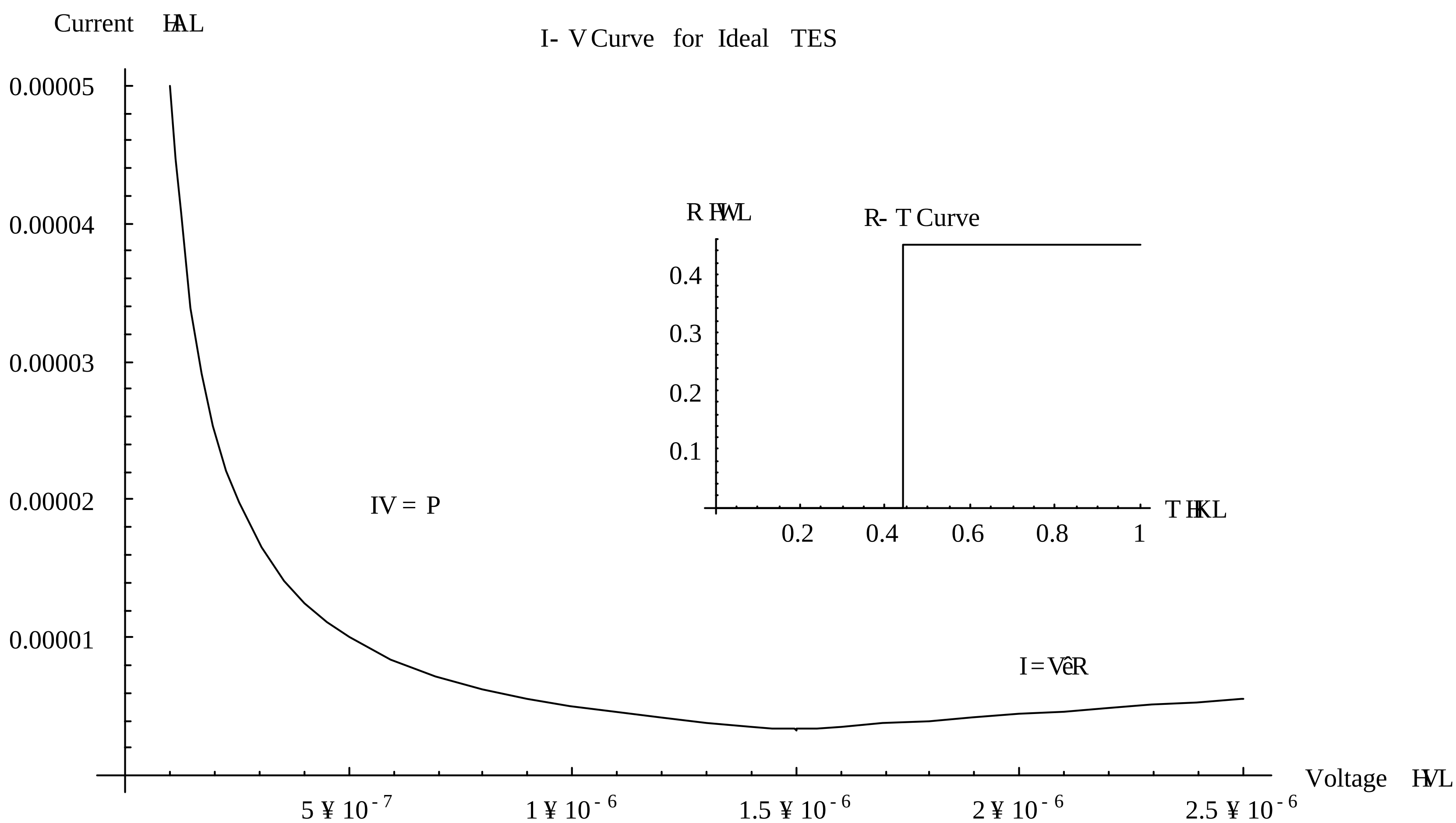
TES Advantages

- High α provides performance advantages
  - Clarke et al. (1977), Mather (1982)
- Devices which couple well to SQUID amps are easily made.
- Voltage-biased devices provide linear response, broad flat frequency response
- With voltage bias, modest variations in Tc across wafer are accomodated
  - Irwin (1995)

SQUID Advantages

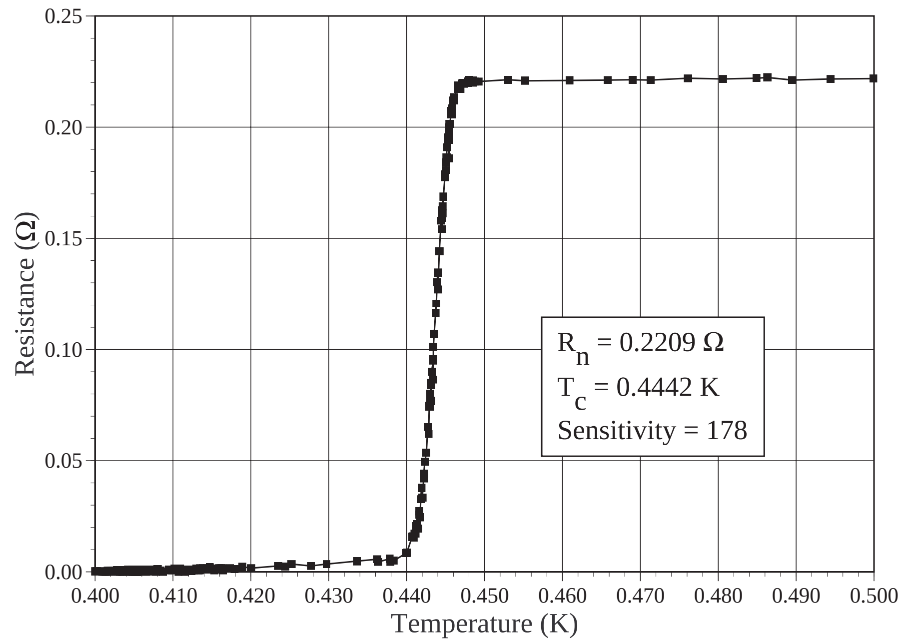
- Low noise
- Very low power
- Can operate at detector temperatures, happy at 4.2 K as well
- Multiplexing offers further advantages for large arrays (Chervenak et al., 1999)

The TES - A Simple Thermal System



Superconducting Transition in Bilayer

- Transition temperature changes with relative thickness of normal metals and superconductors.
- GSFC MoAu bilayer



Key Process Attributes

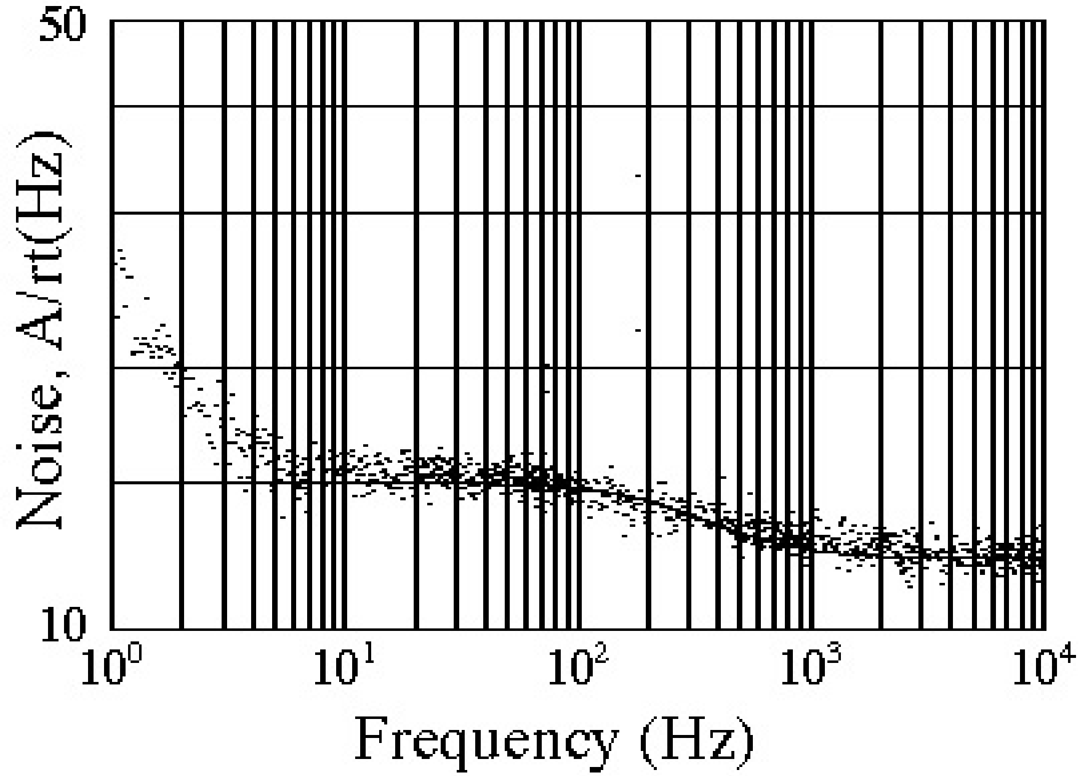
- Bilayer deposition early in process
  - Validate bilayer, only process good wafers
    - Up to ten 4” wafers per deposition; lots of deectors
- Minimization of secondary metallizations
  - Avoid difficult cleaning steps
- High mechanical and electrical yield
- Fast
  - From backthinned wafers to testable detector in < three days.

TES Noise

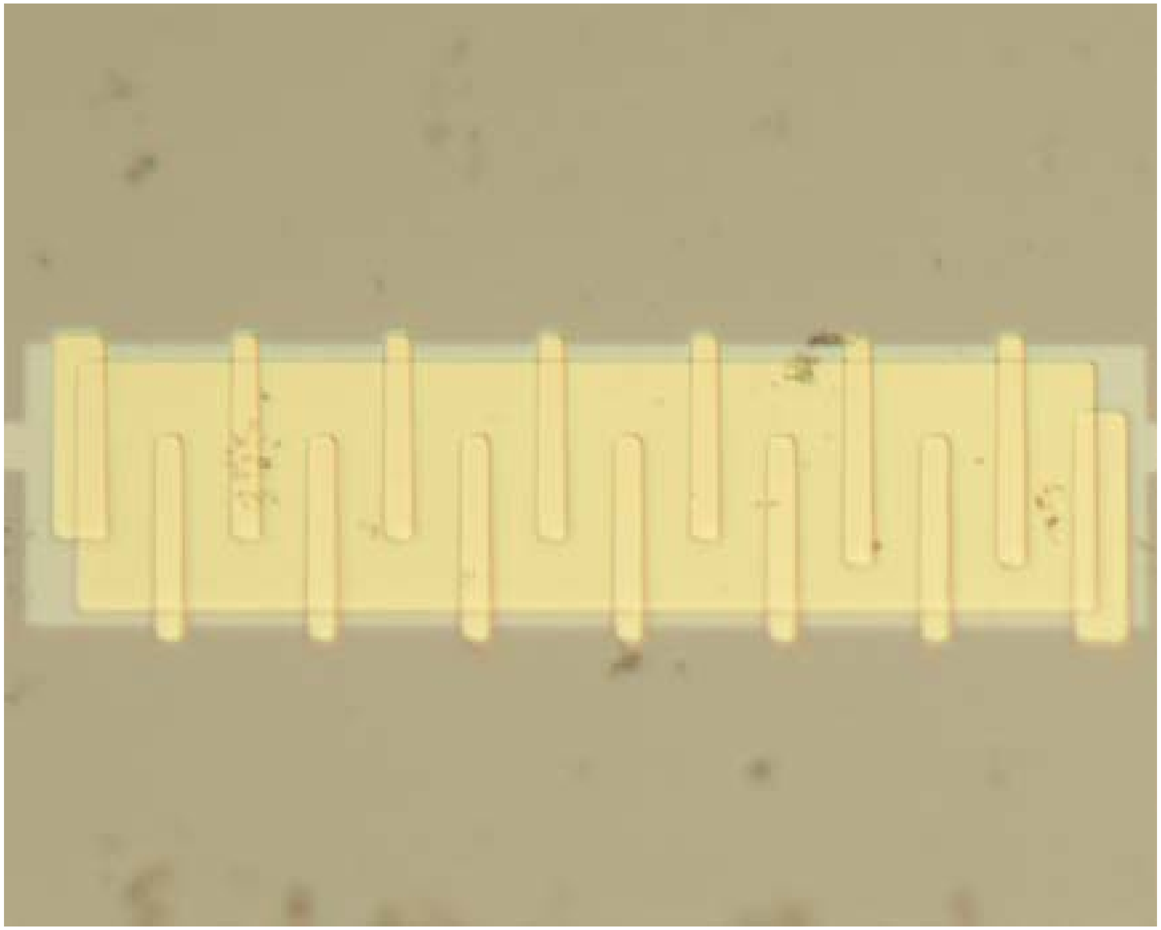
- Several groups have demonstrated near-ideal noise in “IR” type TES detectors
  - Irwin et al., Lee et al., Bock et al.
    - Most have excess out of band high freq noise
- X-ray devices have significant excess noise. (Typically factor of 2) Higher current, Lower R
- Noise appears to be related to flux line dynamics.
  - Edge treatments, changes in geometry reduce noise
- New geometries provide significant reduction in excess high frequency noise
  - NIST (priv. comm.) has independently found similar results with very similar devices

Noise of TES Can Reach Fundamental Limits

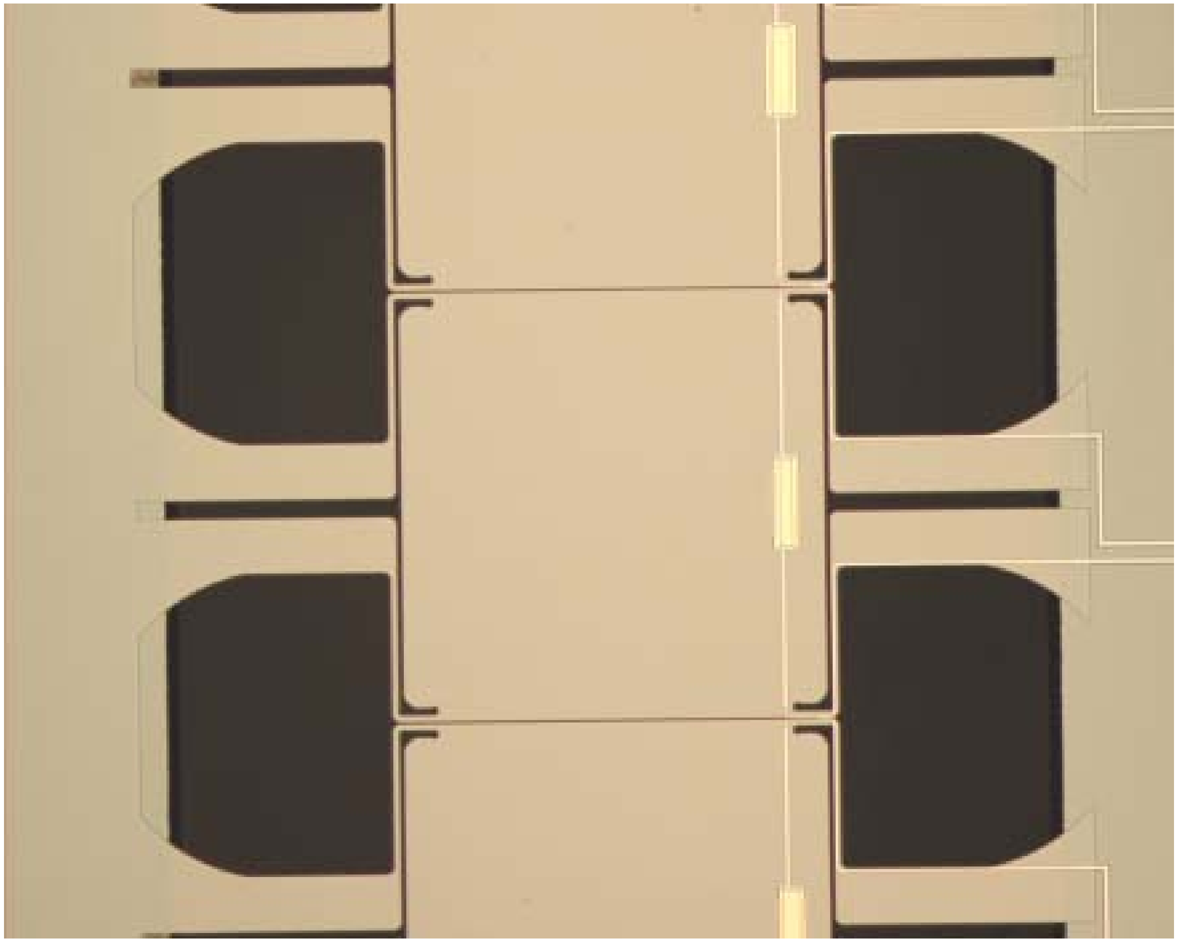
NIST measurement
Of AlAg Bilayer



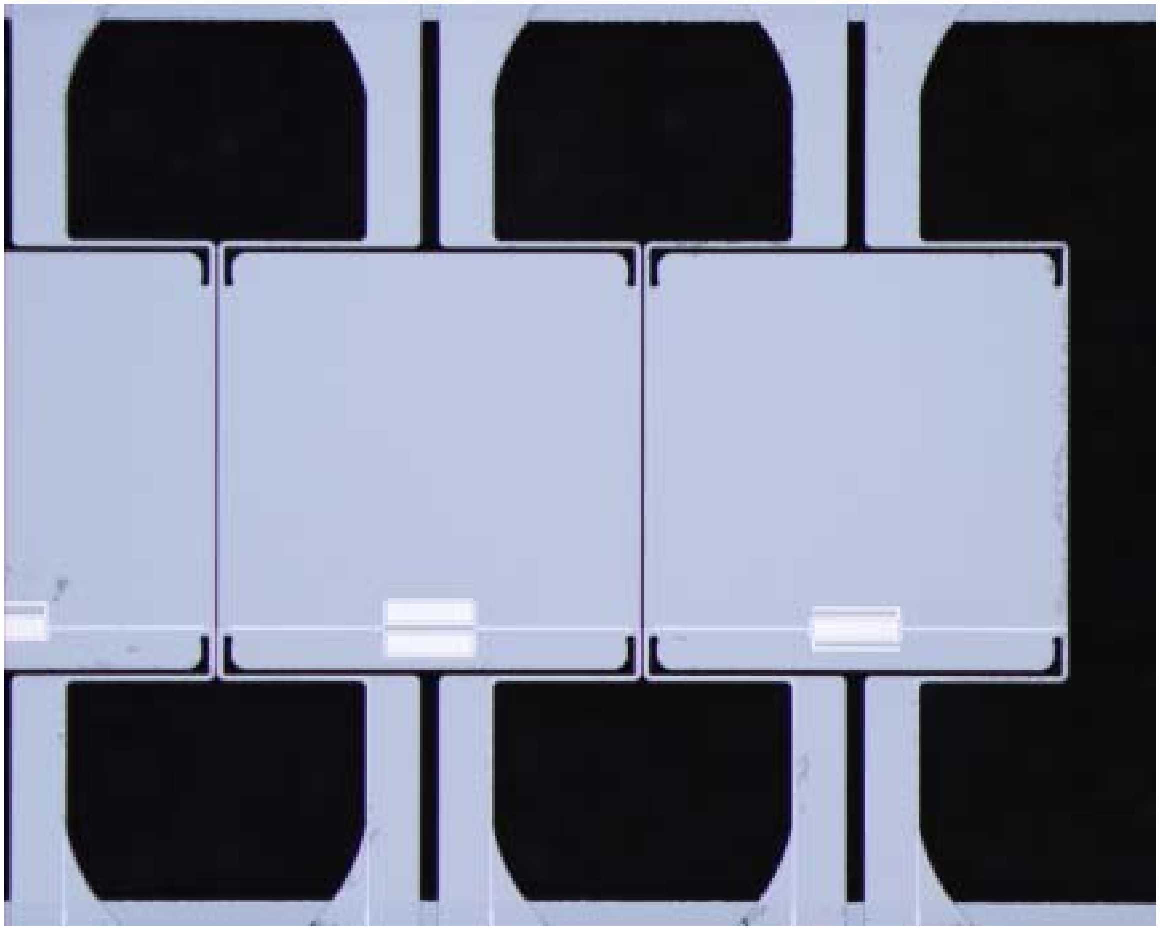
Zebra Geometry Reduces Excess Noise



Micromachined MoAu TES
Si Structure

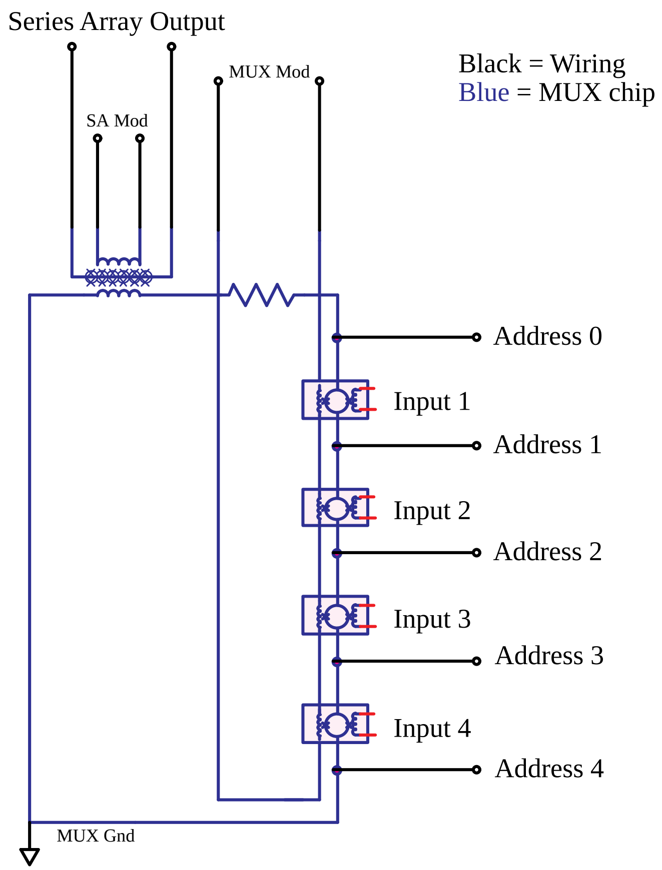


Array Includes a Variety of Thermometer Geometries

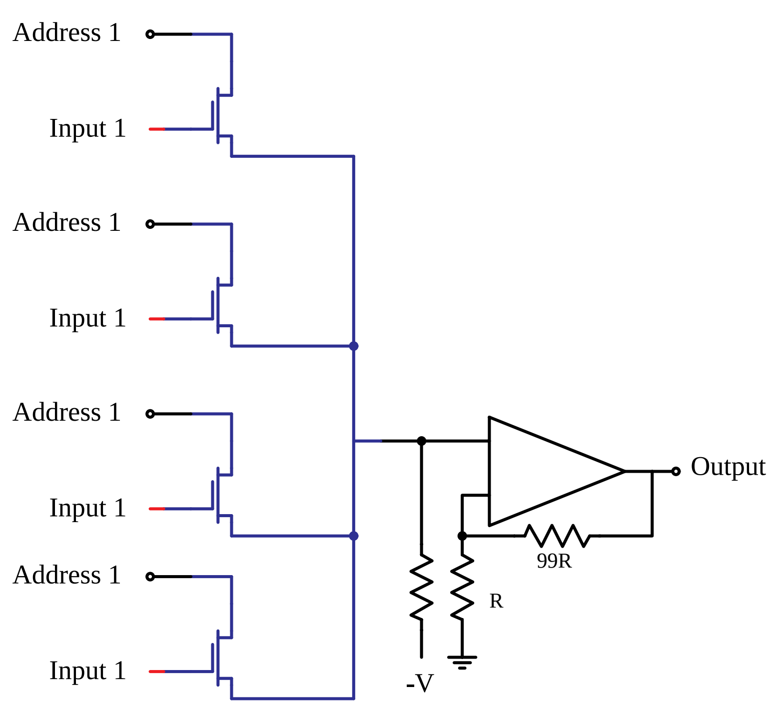


SQUID Mux vs. Mosfet Mux

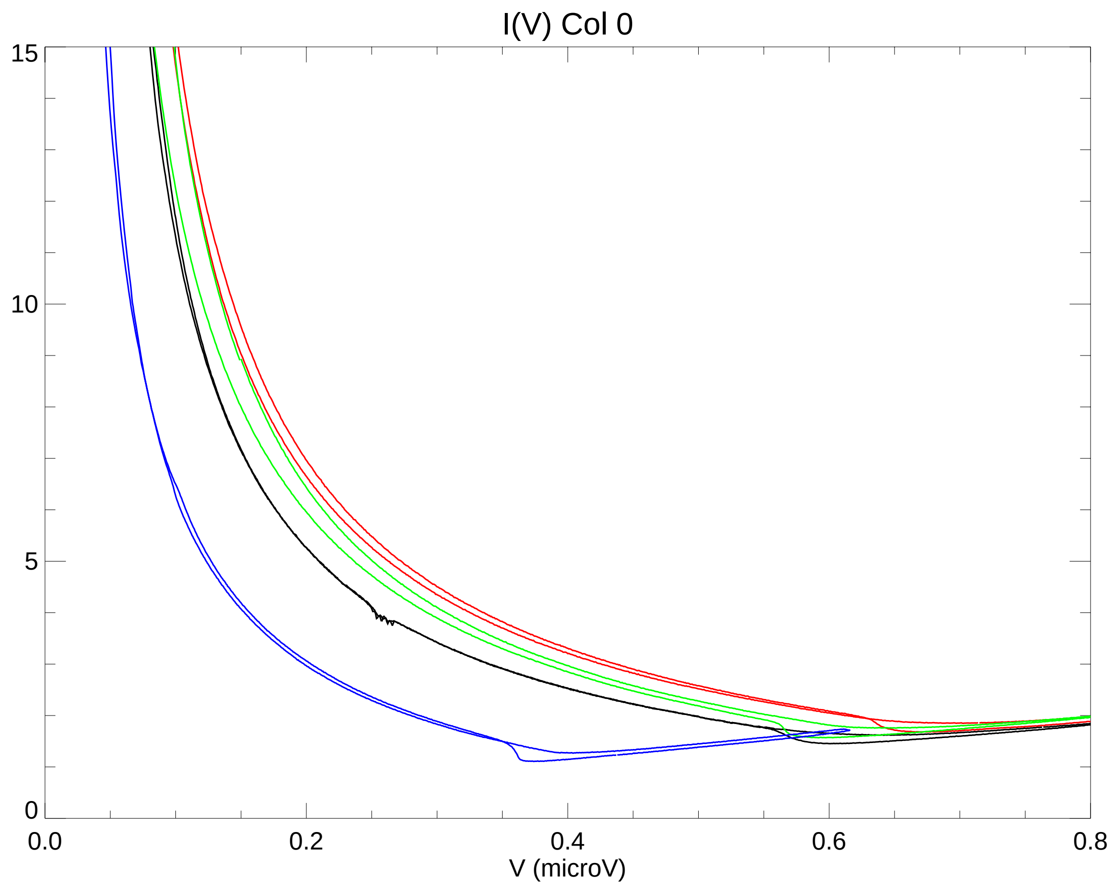
SQUID Mux



Mosfet Mux



I-V Curves of Multiplexed 1 x 8 Array

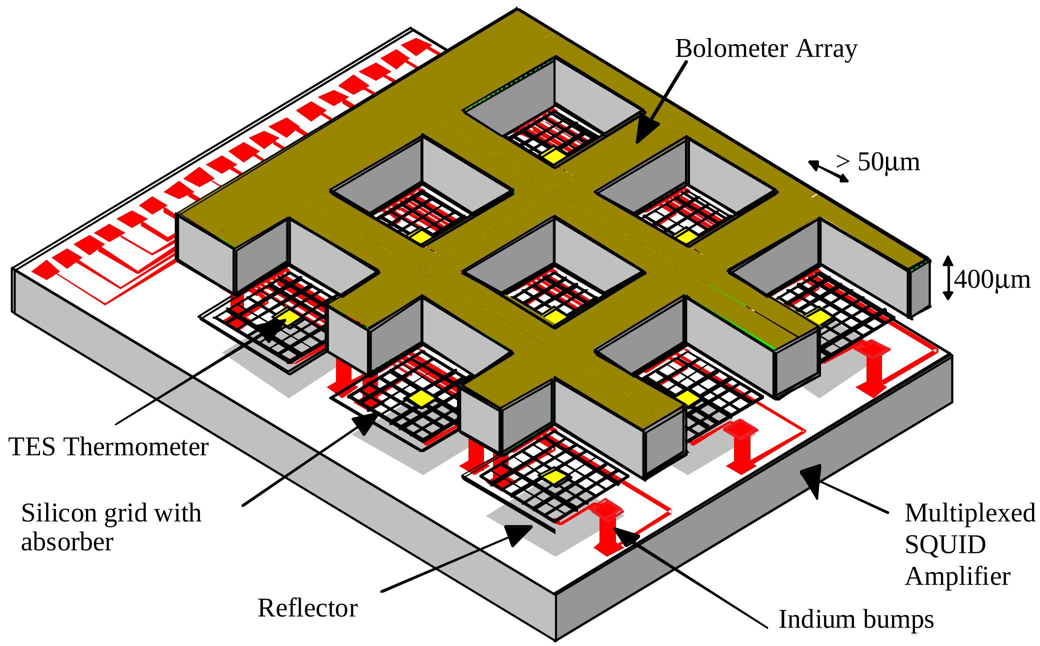


Development Plans

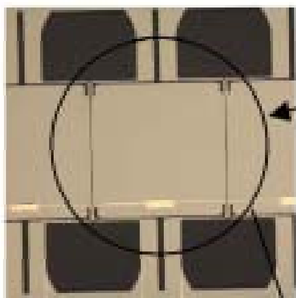
- Pop-up architecture convenient for moderate format arrays in near future.
  - SPIFI
  - SAFIRE
  - GBT
- Planar arrays, alternative coupling methods in longer term

Alternative Configurations Are Under Study for Large Format Arrays

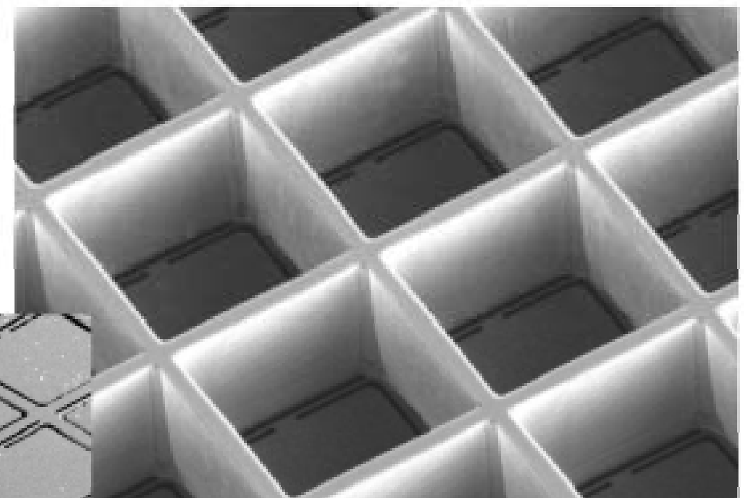
- Superconducting version of Saclay/CEA detector shows promise for scaling to large arrays
- Front end SQUIDs can operate at detector temperature



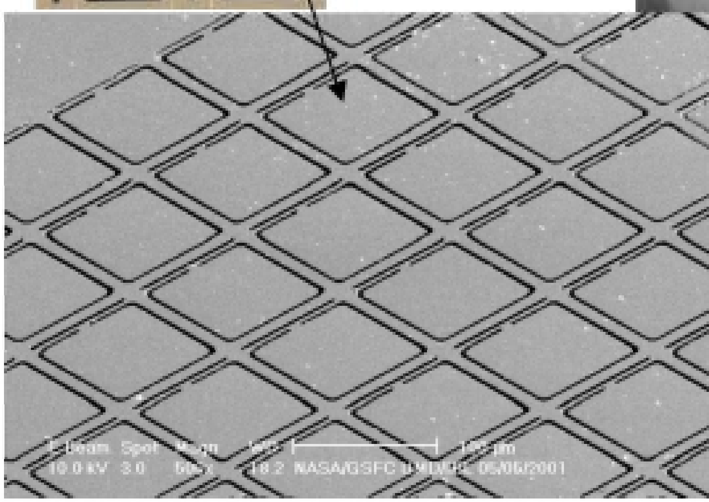
Micromechanical Structures



Bolometers replace shutters

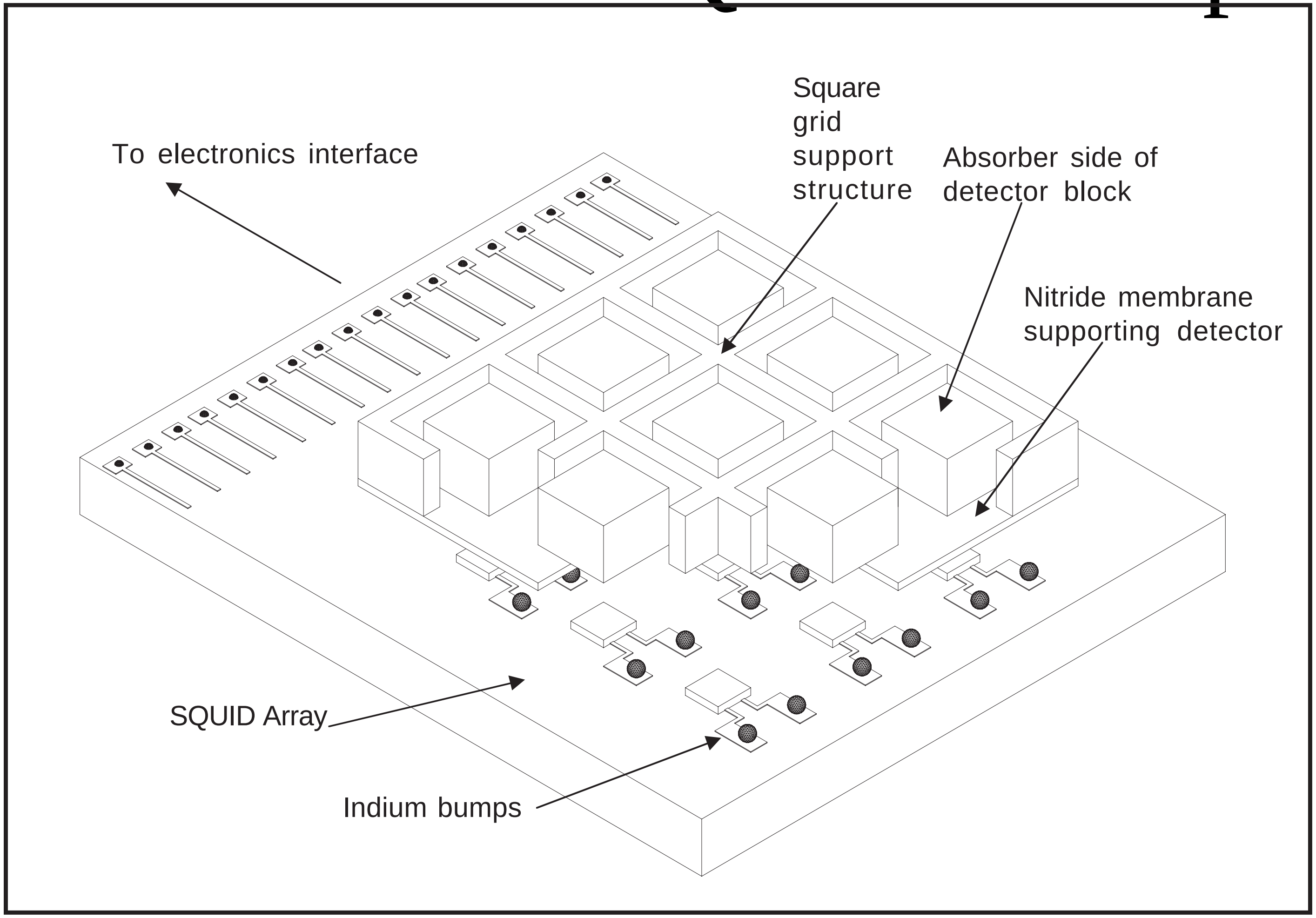


Shutters, viewed from the back through deep RIE wells



2-D array of Shutters, front view

UKATC: SCUBA II TES Bolometers w/ SQUID Multiplexer



Summary

- Multiplexed TES array operation has been demonstrated in lab and FIBRE instrument
  - First light on CSO in the May 2001 (Benford et al.)
- Pop-up versions planned for SAFIRE on SOFIA, SPIFI, GBT, and other applications
- Array technology development is the new front
  - First arrays built in pop-up architecture
  - Planar arrays mid-term goal
    - SCUBA II, Con-X, and our group developing such devices with TDM mux
    - Components - Thru-wafer superconducting vias

What do we need to do to allow Optimization of TES-based Detectors?

- Noise and response as function of:
  - Geometry
  - Boundary conditions
  - Bias power density
  - Normal resistance
  - Resistance under bias
  - Magnetic field conditions
  - Materials
    - Bilayers, magnetic implants, or elemental

Conclusions

- Semiconducting thermometers well understood, fabrication processes in hand
- TES thermometers need more systematic characterization
  - Noise as function of TES parameters
- SQUID multiplexing techniques are maturing rapidly
- Engineering of large arrays is a significant challenge. Significant effort must go into development of architectures and critical components. Con-X may be a pathfinder

FIBRE Test Run

- The Pathfinder module was used in the FIBRE instrument on CSO in May 2001.
- FIBRE is a 350 µm F-P spectrometer, R~1500
- First light under bad conditions, single array.

Microphonics

- The response of the detectors to microphonic response (hard dewar raps) is very small because the detectors are very low impedance. The only response seen was the thermal disturbance in the ^{3}He refrigerator.

Development Program

- In the early 1990s, high performance Si semiconductor bolometers had been built in integrated arrays (KAO, SHARC, XRS).
- We developed designs for scalable large format arrays which provide good sampling and efficient use of focal plane area
  - Developed pop-up architecture to enable scalable close-packed semiconducting detectors with JFETs
  - Planar integrated detectors, like near and mid-IR are the next goal (hard to do with JFETs)
  - To implement a complex engineering program, we need to understand the components well.